The crossover between Aslamazov-Larkin and short wavelength fluctuation regimes in HTS conductivity experiments

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We present paraconductivity (AL) measurements in three different high temperature superconductors: a melt textured $YBa_2Cu_3O_7$ sample, a $Bi_2Sr_2CaCu_2O_8$ epitaxial thin film and a highly textured $Bi_2Sr_2Ca_2Cu_3O_{10}$ tape. The crossovers between different temperature regimes in excess conductivity have been analysed. The Lawrence-Doniach (LD) crossover, which separates the 2D and 3D regimes, shifts from lower to higher temperatures as the compound anisotropy decreases. Once the LD crossover is overcome, the fluctuation conductivity of the three compounds shows the same universal behaviour: for $\epsilon = \ln T/T_c > 0.23$ all the curves bend down according to the $1/\epsilon^3$ law. This asymptotic behaviour was theoretically predicted previously for the high temperature region where the short wavelength fluctuations (SWF) become important.

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It is well known that, owing to strong anisotropy, high critical temperature and low charge carrier concentration, thermodynamic fluctuations play an important role in the explanation of the normal state properties of high temperature superconductors (HTS). Just after the realization of high quality epitaxial single crystal samples, the in-plane fluctuation conductivity was investigated in detail and the Lawrence-Doniach (LD) crossover between three-dimensional (3D) and two-dimensional (2D) regimes (or at least a tendency to it) was observed in the vicinity of T_c in the majority of HTS compounds. Analogous phenomena were observed in magnetic susceptibility, thermoconductivity[1] and other properties of HTS.

Let us recall that LD crossover takes place in the temperature dependence of in-plane conductivity and it is related to the fact that fluctuative Cooper pairs motions change from 2D to 3D rotations. It takes place at the temperature T_{LD} which is defined by the condition $\xi_c(T_{\mathrm{LD}}) \approx s$, where ξ_c is the coherence length and s is the interlayer distance. Nevertheless, the LD crossover in the temperature dependencies of different characteristics does not exhaust all possibilities: additional crossovers can be observed in HTS compounds. For instance, another kind of crossover (0D $\rightarrow$ 3D) can take place in c-axis paraconductivity temperature dependence, at the same temperature T_{LD}. It is due to the fact that the pair propagation along c-axis has a zero-dimensional character relatively far from T_c and it changes into a three-dimensional rotation in the immediate vicinity of the transition. This effect was predicted[2] and observed[3] in fully oxygenated YBCO samples while in BSCCO samples it is masked by the increase of resistivity due to fluctution density of states renormalization. Below we will remind the reader of the possible kinds of crossover phenomena taking place in layered superconductors and finally we will present the experimental evidences of the crossover related to the breakdown of Ginzburg Landau (GL) approximation, due to the importance of short wavelength fluctuations.

How the LD crossover appears in the framework of the GL theory can be shown explicitly considering the model of an open electron Fermi surface which, for instance, can be chosen in the form of a "corrugated cylinder"[4]. In this case the energy spectrum has the form

$$\xi(\mathbf{p}) = \epsilon_0(\mathbf{p}) + J\cos(p_\perp s) - E_{\mathrm{F}}, \tag{1}$$

where $\epsilon_0(\mathbf{p}) = \mathbf{p}^2/(2m)$, $p \equiv (\mathbf{p}, p_\perp)$, $\mathbf{p} \equiv (p_x, p_y)$ is a two-dimensional, intralayer wavevector, and J is an effective hopping energy. The Fermi surface is defined by the condition $\xi(p_{\mathrm{F}}) = 0$ and E_{F} is the Fermi energy. This spectrum is the most appropriate for strongly anisotropic layered materials where $J/E_{\mathrm{F}} \ll 1$.

In the framework of the Ginzburg-Landau theory for an isotropic spectrum, the fluctuation contribution to the free energy of a superconductor above the critical temperature can be presented as the sum over long wavelength fluctuations[5]:

$$F = -T\sum_{\mathbf{q}} \ln \frac{\pi T}{\alpha(\epsilon + \eta \mathbf{q}^2)}. \tag{2}$$

where α and η are the coefficients of GL theory. In the expression (2) $\epsilon = \ln(T/T_c) \simeq (T - T_c)/T_c \ll 1$ is supposed. The term $\eta\mathbf{q}^2$ in (2) is actually the result of angular averaging over the isotropic Fermi surface of $(\mathbf{v}\cdot\mathbf{q})^2$ (up to

some dimensional coefficient) and in the case of anisotropic spectrum (1) must be substituted by the more sofisticated expression including the additional dependence on $q_\perp$:

$$\left\langle (\mathbf{v}\cdot\mathbf{q})^2 \right\rangle = \left\langle [\xi(\mathbf{p}) - \xi(\mathbf{q}-\mathbf{p})]^2 \right\rangle = \frac{1}{2}\left(v_{\mathrm{F}}^2\mathbf{q}^2 + 4J^2\sin^2(q_\perp s/2)\right) \tag{3}$$

Formally the crossover temperature is defined by the analysis of the denominator in the expression (2). Evidently, in the strictly 2D case, the hopping integral $J \to 0$ and the integration over $q_\perp$ is reduced to the redefinition of the density of states only. The crossover in the fluctuation behaviour takes place when the integration over the transverse variable becomes important and changes the temperature dependence of the appropriate fluctuation correction. This happens, evidently, when the transversal part reaches the reduced temperature ϵ or, in other words, when $\xi_{\mathrm{c}}(T_{\mathrm{LD}}) \approx s$. For not too anisotropic compounds, such crossover can be delayed up to temperatures high enough, far from the immediate vicinity of the transition.

Analogous phenomena can be also observed in the presence of a magnetic and even electric field[6]. The reason for this fact can be understood from the following consideration. The integrand function in (2), in its exact formulation, is nothing else than the fundamental solution of the Maki-De Gennes equation (see, for instance, the review article of K. Maki in[7]). When some external field is applied, the eigen-value of the unperturbed Hamiltonian is renormalized and, starting from some value of the interaction strength, the pole in q-dependence is determined more by the renormalization of the eigen-function than by the reduced temperature ϵ.

Further, the presence of an **ac** electromagnetic field leads to the appearance of $-i\omega$ side by side with the energy eigen-value in the Maki-De Gennes equation[7]. This results in a possible crossover in the frequency dependence of fluctuation conductivity[8–10].

Another kind of crossover is related to the geometry of the samples. Let us suppose that the epitaxial film of layered superconductor consists of several layers only. In this case, very near to T_{c}, the transverse size of Cooper pairs fluctuations can exceed the film thickness and the class of possible pairs motions is again reduced to that of 2D rotations[11]. This kind of crossover cannot be easily observed in HTS films because of the extremely short coherence length, but it becomes observable for conventional superconducting thin films or in artificial superlattices of materials with large coherence length.

The last kind of crossover, which we would like to discuss here, is related to the breakdown of the GL approach in describing the fluctuations relatively far from the transition where the assumption of the domination of long wavelength fluctuations contribution is no longer valid. The generalization of the fluctuation conductivity theory for high temperature region has been already analysed[12]. Namely the short wavelength fluctuations have been taken into account and the universal formula for paraconductivity has been obtained

$$\sigma_{\mathrm{fl}}^{2\mathrm{D}} = \frac{e^2}{16\hbar s} f(\epsilon). \tag{4}$$

In the GL region of temperature, where $\epsilon \ll 1$, $f(\epsilon) = 1/\epsilon$ and the result coincides with the well known AL one. In the opposite case $\epsilon \gg 1$, for clean 2D superconductors, $f(\epsilon) \sim 1/\epsilon^3 = 1/\ln^3(T/T_{\mathrm{c}})$ was carried out. In the theoretical consideration it was natural to assume formally the very rigid restriction $\epsilon \gg 1$ for the validity of the latter asymptotic behaviour. Nevertheless, as it will be seen below, in experiments the crossover to this asymptotic behaviour takes place universally for all the samples investigated at $\epsilon \sim 0.23$ and this can be attributed to some particularly fast convergence of the integrals in the expression of $f(\epsilon)$.

The long tails in the in-plane fluctuation conductivity of HTS materials have been observed frequently. One of the efforts to fit the high temperature paraconductivity with the extended AL theory results was undertaken in[13] where the deviation of the excess conductivity from AL behaviour was analysed for three $Bi_2Sr_2CaCu_2O_8$ epitaxial films. Very good fit with the formula (4) was found in the region of temperatures $0.02 \lesssim \epsilon \lesssim 0.14$. We show here that the careful analysis of the higher temperature region (just above the edge of the region investigated in[13]) allows to observe the surprisingly early approaching to the SWF asymptotic regime (at the reduced teperature $\epsilon^* \sim \ln(T^*/T_{\mathrm{c}}) \sim 0.23$).

We have performed resistivity measurement of three different HTS compounds: a melt textured $\mathrm{YBa_2Cu_3O_7}$ sample (Y123), a $\mathrm{Bi_2Sr_2CaCu_2O_8}$ (Bi2212) thick film and a highly textured $\mathrm{Bi_2Sr_2Ca_2Cu_3O_{10}}$ (Bi2223) tape. The Y123 was obtained by melting[14]; the sample was cut in a nearly regular parallelepipedal shape with a cross section of about 4 mm^2 and a length of 7 mm. The resistivity measurements were performed from 85 to 330 K. The critical temperature, defined as the point where the temperature derivative is maximal, is 92 K; $\rho_{\mathrm{N}}(100K) = 120\ \mu\Omega cm$, where ρ_{N} is the resistivity in the normal state extrapolated from the high temperature region where ρ is linear. The Bi2212 film was prepared by a liquid phase epitaxy technique[15]. The film has a thickness of about 1 μm. The resistivity measurements were performed from 80 to 170 K. The critical temperature was estimated to be 84.2 K and $\rho_{\mathrm{N}}(100\ K) = 150\mu\Omega cm$. The Bi2223 tape was obtained by means of the power in tube procedure, as described elsewhere[16]. The thickness of the oxide filament inside the tape was about 30 μm; the filament turned out to be

strongly textured (rocking angle $\approx 8^\circ$) with the c-axis oriented perpendicular to the tape plane. The resistivity measurements were performed in the range from 100 to 250 K, after removing the silver sheathing chemically. The critical temperature was estimated to be 108 K and $\rho_{\rm N}(100K) = 300\ \mu\Omega cm$. We ascribe this high value of $\rho_{\rm N}$ to different causes: first, the grain boundaries may determine a resistance in series with the grain resistance; second, the chemical treatment may have damaged the surface of the sample and the effective cross section of the superconductor can be decreased.

The excess conductivity was estimated by subtracting the background of the normal state conductivity $\sigma_{\rm N} = 1/\rho_{\rm N}$. The evaluation of $\rho_{\rm N}$ was made with particular accuracy; in fact, starting the interpolation at a certain temperature corresponds to forcing σ_{fl} to vanish artificially at such temperature. Therefore, we need to estimate $\rho_{\rm N}$ at a temperature as large as possible and to verify that $\rho_{\rm N}$ does not depend on the temperature range where the interpolation is performed. In the case of Y123 sample the resistivity shows a linear behavior from 160 to 330 K. In this range we have verified that $\rho_{\rm N}$ does not change by shifting the interpolation temperature region.

Therefore, for the Y123 sample, the upper limit of ϵ at which the excess conductivity may be analysed is $\epsilon_{\rm up} \approx ln(160/92) = 0.55$. In an analogous way we obtain $\epsilon_{\rm up} \approx 0.46$ and 0.51 for Bi2212 and Bi2223, respectively.

In Fig. 1, in a log-log scale, we plot $\sigma_{\rm fl}\left(\dfrac{16hs}{2\pi e^2}\right)$ as a function of ϵ for the three samples; the solid line represents $1/\epsilon$, the dashed line $0.055/\epsilon^3$ and the dotted line is $3.2/\sqrt{\epsilon}$. The interlayer distance s is considered as a free parameter and it has been adjusted so that the experimental data can follow the $1/\epsilon$ behaviour in the ϵ region where the AL behavior is expected.

We can see that all the curves exhibit the same general behaviour. The region where the 2D $1/\epsilon$ behaviour is followed, has different extension for each compound, depending on its anisotropy, and at $\epsilon \approx 0.23$ all the curves bend downward and follow the same asymptotic $1/\epsilon^3$ behaviour.

We discuss now some features in detail:

1) The interlayer distance values we find are the following: for Y123 we obtain $s \approx 13$ $\AA$ which must be compared with the YBCO interlayer distance that is about 12 $\AA$; for Bi2212 we obtain $s \approx 11$ $\AA$ to be compared with 15 $\AA$, and for Bi2223 we obtain $s \approx 25$ $\AA$ to be compared with 18 $\AA$. The differences in the interlayer distance evaluation are all compatible with the uncertainty on the geometrical factors. We point out that the smallest error is for Y123 (about 10%) that is a bulk sample with a well defined geometry. Larger errors are found for the Bi2212 thick film (about 30%), for which the evaluation of the thickness is rough, and for the Bi2223 tape (about 40%) for which an overestimation of the cross section of the tape is possible, as we mentioned above. We conclude that the AL behaviour is well followed.

2) On the low ϵ value side ($\epsilon < 0.2$) the three compounds show different behaviours due to the different extension of the AL region. The least anisotropic compound, Y123, for $\epsilon < 0.1$ bends going asymptotically to the 3D behaviour ($1/\epsilon^{0.5}$) showing the LD crossover at $\epsilon \approx 0.09$; the Bi2223 sample starts to bend for $\epsilon < 0.03$ while the most anisotropic Bi2212 in the overall ϵ range considered shows the 2D behaviour.

3) On the high ϵ value side, starting from the AL behaviour, the curves show a crossover at about $\epsilon = 0.23$ and then bend downward following the asymptotic $1/\epsilon^3$ behaviour. At the value $\epsilon \approx 0.45$ all the curves drop indicating the end of the observable fluctuation regime. This value is lower than the above reported $\epsilon_{\rm up}$ values, at which the fluctuation conductivity comes out to be zero.

To conclude: we have observed in three different HTS compounds the universal high temperature behaviour of the in-plane conductivity that manifests itself in the 2D regime, once the LD crossover is passed. Beyond the AL regime all the curves reach soon the SWF $1/\epsilon^3$ regime. For all the compounds the crossover occurs at the same point $\epsilon \approx 0.23$, which corresponds to $T \approx 1.3T_{\rm c}$ and, therefore, is experimentally well observable. The universality of the paraconductivity behaviour is much more surprising if we consider that it has been observed in three compounds with different crystallografic structure and anisotropy, and moreover prepared by means of very different techniques.

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FIG. 1. $\sigma_{\rm fl}\left(\frac{16hs}{2\pi e^2}\right)$ vs ϵ for Y123 (triangle), Bi2212 (square) and Bi223 (circlet); the solid line is $1/\epsilon$, the dashed line $0.055/\epsilon^3$, and the dotted line is $3.2/\sqrt{\epsilon}$